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TITLE OF THE INVENTION

PRODUCTION RISER WITH PRE-FORMED CURVES FOR ACCOMMODATING VESSEL MOTION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a Continuation-in-Part of co-pending application no. 10/213,963; filed August 7, 2002, the disclosure of which is incorporated herein by reference.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable

BACKGROUND OF THE INVENTION

This invention is generally related to risers that convey fluid from producing wells on the seafloor to a floating structure or vessel on the sea surface. This invention is also related to a conduit that is fixed to the seafloor, which must accommodate the motion of a floating body, structure, or vessel that is connected to it.

In offshore drilling and production operations carried out from a floating vessel, fluid is conveyed from wells on the seafloor to the vessel stationed on the surface by a conduit often referred to as a "riser." Various methods and mechanisms are used to reduce stresses in risers that are affixed to the moving vessel on the surface and the stationary wellhead at the seafloor. These include using flexible hose for the riser in lieu of steel pipe, supporting a steel riser with hydraulic or elastomeric tensioners that accommodate the relative movement of the vessel, buoyancy cans that support the pipe at the top and allow the vessel to move (as shown in, for example, U.S. Patent No. 4,702,321, incorporated herein by reference) or some combination of these techniques. Another method is by using a steel catenary riser (often referred to as a "SCR"), which comprises an extension of the steel riser pipe a sufficient horizontal distance from the vessel such that the pipe forms a rather deep catenary curve. Depending on a number of

factors, the SCR can be designed to accommodate some vessel motion.

The above methods all have disadvantages and limitations. For example, flexible hose is costly, cannot withstand external compressive loads without internal stiffening, and requires bend-restrictor devices at the terminations. The SCR are much less costly and have a long record of reliability; however, their shortcoming lies in motion compensation. The tensioners and buoyancy cans are expensive, and they both require a flexible hose (referred to as a "jumper line") to accommodate the relative motion between the top of the riser, which sometimes includes a "christmas tree," and a flow manifold (fixed to the vessel).

One proposed system that attempts to address the aforementioned problems is disclosed in US 5,553,976 – Korsgaard. This reference discloses a riser formed into a helical or sinusoidal configuration for decoupling axial stresses in the riser resulting from internal fluid pressure and/or external tension forces. The riser in this system, however, requires a plurality of elastic tensioning members that extend along the longitudinal direction of the riser, and that are secured to the riser at spaced intervals. The need for such tensioning members increases the cost of manufacturing and installing such systems.

There is therefore a need for a relatively low-cost, simple riser that compensates for the motion of a floating vessel, and that does so without the need for separate tensioning members attached to the riser.

SUMMARY OF THE INVENTION

The above issues are addressed by the present invention that employs a self-tensioning curved riser in a system for establishing fluid communication between a floating body and a wellhead on the seafloor. The system comprises fluid-conducting means for fluidly connecting the floating body and the wellhead, wherein the fluid-conducting means defines a major axis essentially extending from about the floating-body to about the wellhead. The system further comprises a means for absorbing and releasing energy in response to the heave and surge of the floating body that flexes in a direction essentially parallel to the major axis. In the preferred embodiments of the

invention, the fluid-conducting means comprises a self-tensioning steel riser, and the means for storing and releasing energy comprises a series of pre-formed curves in the steel riser. In some embodiments, the series of pre-formed curves comprises a series of single-planar, preformed curves in the riser. These single-planar curves comprise arcs having a substantially constant radius of curvature in one embodiment and sinusoidal curves in another embodiment. In some other embodiments, the series of pre-formed curves comprises helical pre-formed curves.

In accordance with specific embodiments of the invention, an apparatus for establishing a fluid connection between a floating body and a wellhead fixed to the seafloor comprises a riser pipe and a series of pre-formed curves in the riser pipe that defines a substantially linear axis between the floating body and the wellhead. In some embodiments the series of pre-formed curves comprises multi-planar curves, which in one embodiment comprises helical shaped curves. In some other embodiments, the series of pre-formed curves comprises single-planar curves, which in one embodiment comprises sinusoidal curves. The riser pipe is made of steel in some embodiments, but in some embodiments, the pre-formed curves may be of a different material than the remainder of the riser pipe.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of an exemplary embodiment of riser with a series of pre-formed curves.

FIG. 2 is a side view of an exemplary embodiment with a pre-formed helical curve.

FIG. 3 is a side view of an exemplary embodiment with a pre-formed curve in a single plane.

DETAILED DESCRIPTION OF THE INVENTION

According to one exemplary embodiment of the invention, seen in Figure 1, a fluid conducting conduit between a floating structure or vessel ("floating body") 16 and a

wellhead 12 on the sea floor 13 is provided by a riser pipe 14, at least a substantial portion of which is formed with a series of pre-formed curves 10. These curves 10 accommodate the stress generated by the motion of the floating body 16. The pre-formed curves 10 flex in response to the motion of the floating body 16, so that the forces generated by the motion of the floating body 16 are not transmitted to the wellhead 12. By using these pre-formed curves 10, a single, steel riser pipe 14 becomes feasible to connect the floating-body with the wellhead 12, without the need for a using catenary curve. The riser pipe 14 is a rigid conduit, preferably made of a suitable steel alloy or some other similar alloy, as would be well-known to those skilled in the pertinent arts.

By accommodating the motion of the floating body 16, the preformed curves 10 also eliminate the need for a flexible section of pipe to connect the riser pipe 14 and the floating-body 16. Using a metal (particularly steel) riser pipe 14 further eliminates the need for the external stiffening associated with using a flexible pipe section because the steel can withstand the external compressive loads exerted by the environment. In one embodiment, the pre-formed curves 10 are fashioned from a different material than the remainder of the riser pipe 14.

By absorbing the forces exerted by the floating body 16 without using a catenary curve, the pre-formed curves 10 also eliminate the need for additional buoyancy devices. As a result, in one embodiment, the riser pipe 14 connecting the wellhead 12 to the floating body 16 is only suspended from the floating body 16. In one embodiment, the suspension from the floating body 16 supports the entire weight of the riser pipe 14, while in another embodiment, part of the weight of the riser pipe 14 is supported by the riser pipe 14 itself.

As shown in Figure 1, while mooring lines 15 may be provided to attach the floating body 16 to the sea floor, the riser pipe 14 is self-tensioning and thus needs no external anchoring or tensioning means attached to it. This self-tensioning, or pre-tensioning, is accomplished by first lowering the riser pipe 14 to the seafloor 13 and anchoring it at the wellhead 12. This is typically accomplished by means such as derrick or any conventional equivalent apparatus (not shown) on the floating body 16. Tension is

then applied to the upper end of the riser pipe 14 by means of the derrick (or equivalent apparatus), and upper end of the riser pipe 14, in its pre-tensioned state, is secured to the appropriate structure on the floating body by conventional means, as is well-known in the art. Thus, the riser pipe 14, when installed, is in a self-tensioned or pre-tensioned state, and needs no external tensioning means.

In some embodiments, the pre-formed curves 10 do not affect the overall orientation or direction of the riser pipe 14. Therefore, in one embodiment, the floating body 16 from which the riser pipe 14 is suspended is positioned directly above the wellhead 12. The riser pipe 14 thereby defines an axis 21 essentially from about the floating body 16 to about the wellhead 12. For the riser pipe 14 to accommodate the motion of the floating body 16, the pre-formed curves 10 flex in a direction essentially parallel to the axis 21 defined by the riser pipe 14. In another embodiment, positioning the floating body 16 closer to the wellhead 12 simplifies the installation and design of the sub-sea systems, in part by enabling a vertical connection between the riser pipe 14 and the wellhead 12. Tools pass more easily through a vertical wellhead 12 connection than through a horizontal connection.

In one embodiment, the portion of the riser pipe 14 in which the series of pre-formed curves 10 is formed is at or near the bottom end of the riser pipe 14, and is thus connected between the wellhead 12 and the remainder of the steel riser pipe 14. In other embodiments, the series of pre-formed curves 10 extends along substantially the entire length of the riser pipe 14, from the wellhead 12 to the floating body 16. In still other embodiments, segments of relatively straight riser pipe 14 are on either end of the portion having the series of pre-formed curves 10.

In the example shown in Figure 1, the riser pipe 14 connects with a floating body 16 (in this example, a SPAR-type semi-submersible), and has a series of pre-formed curves 10 at its lower end, near the juncture with the wellhead 12. Other types of floating body 16 that can be used with the invention include floating production storage and offloading (FPSO) systems, semi-submersible platforms, tension leg platforms, and others known to those of ordinary skill in the art. The connection between the wellhead

12 and the floating body 16 provided by the self-tensioning curved riser allows fluid communication therebetween. In some examples, this connection also allows tools to be passed from one section to another, and in one specific embodiment, the riser pipe 14 is raised using some lifting means (not shown) located on the floating body 16, stretching the series of pre-formed curves 10 and allowing tools to pass more easily through the series of preformed curves 10.

Referring now to Figures 2 and 3, examples of pre-formed curves 10 are shown. In Figure 2, the pre-formed curves 10 are three-dimensional curves forming an open coil, which advantageously may be a helical curve. As shown in Figure 2, the vertical distance between equivalent points in the helical curve is called the curve spacing 17, and the curve diameter 18 describes the diameter of the cross-sectional area of the curve. In some embodiments, the curve spacing 17 is at least double the curve diameter. In one embodiment, the curve spacing 17 increases with the distance along the axial length of the riser 14 above the seafloor.

The characteristics of one set of exemplary embodiments of a riser pipe 14 with helical pre-formed curves 10 are shown in Table I below.

Table 1 - Riser Pipe Embodiments With Helical Pre-Formed Curves

No	L	A	TL	OD	Wt	D/t	RF	RFr	St	Kr	PS_{ksi}	PS_{psf}	$P_{ksf}*10^2$	L_{30ksi}
1	30	3.4	240	6.625	0.4321	15.3	24.6	1.0	1.2	1.0	127.1	1.83E+07	183.0	1016.7
2	20	3.4	240	6.625	0.4321	15.3	19.5	0.8	1.0	0.8	85.1	1.23E±07	122.5	680.6
3	30	2	240	6.625	0.4321	15.3	84.6	3.4	4.2	3.4	294.4	4.24E+07	424.0	2355.6
4	30	5	240	6.625	0.4321	15,3	9.2	0.4	0.5	0.4	59.0	8.49E÷06	84.9	471.7
5	40	3.4	240	6.625	0.4321	15.3	27.5	1.1	1.4	1.1	153.9	2.22E+07	221.6	1231.1
6	20	3.4	240	6.625	0.2161	30.7	10.8	0.4	0.5	0.4	88.1	1.27E+07	126.8	704.4
7	30	2	240	6.625	0.2161	30.7	46.9	1.9	2.3	1.9	304.9	4.39E+07	439.0	2438.9
8	30	3.4	240	6.625	0.2161	30.7	13.6	0.6	0.7	0.6	131.3	1.89E+07	189.0	1050.0

9	30	5	240	6.625	0.2161	30.5	5.1	0.2	0.3	0.2	61.0	8.79E+06	87.9	488.3
10	40	3.4	240	6.625	0.2161	30.7	15.3	0.6	0.8	0.6	159.0	2.29E+07	229.0	1272.2
11	30	3.4	240	8	0.5229	15.3	52.1	2.1	2.6	2.1	153.6	2.21E+07	221.3	1229.2

L represents the curve spacing measured in feet.

A represents the curve radius measured in feet.

TL represents the total length of the curve used for simulation purposes measured in feet.

OD represents the outer diameter of the riser pipe measured in inches.

Wt represents the wall thickness of the riser pipe wall measured in inches.

D/t represents the ratio of the outer diameter to the thickness of the riser pipe wall.

RF represents the reaction force necessary to displace the top of the planar sine wave riser 20 feet.

RFr represents a normalization of the reaction forces to a base case scenario.

K represents the stiffness of the riser model.

Kr represents a normalization of the stiffness to a base case scenario.

PS_{ksi} represents the peak stress in kips per square inch.

PS_{psf} represents the peak stress in pounds per square foot.

$PS_{ksf*100}$ represents the peak stress in kips per square foot multiplied by 100.

L_{30ksi} represents the length of a curved section with necessary to maintain a maximum stress of 30 ksi in the riser.

Figure 3 shows an exemplary embodiment in which the series of pre-formed curves 10 comprises curves in a single plane. In some embodiments, these single-planar, pre-formed curves 10 are sinusoidal; and, in other embodiments, the pre-formed curves 10 have semi-circular or other shapes. Combinations of such shapes of varying complexity are included in still further example embodiments. In one embodiment, the pre-formed curves 10 comprise several connected segments of pipes. As shown in Figure 3, the vertical distance between equivalent points in the sinusoidal curve is called the wavelength 19, and the amplitude 20 describes the width of the curve.

The characteristics of one set of exemplary embodiments of a sinusoidal riser pipe 14 are shown in Table 2 below.

Table 2 .Riser Pipe Embodiments With Sinusoidal Pre-Formed Curves

No	L	A	TL	OD	Wm	D/t	RF	RFr	St	Kr	PS_{ksi}	PSpsf	$P_{ksi*102}$	L_{30ksi}
1	30	2.0	210	6.625	0.4321	15.3	425.4	2.8	21.3	2.8	815.5	1.17E+08	1174.3	5708
2	30	3.4	210	6.625	0.4321	15.3	150.4	1.0	7.5	1.0	461.9	6.65E+07	665.1	3233
3	20	3.4	220	6.625	0.4321	15.3	135.5	0.9	6.8	0.9	411.0	5.92E+07	591.8	3014
4	40	3.4	200	6.625	0.4321	15.3	85.8	0.6	4.3	0.6	508.8	7.33E÷07	732.7	3392
5	30	3.4	420	6.625	0.4321	15.3	72.1	0.5	3.6	0.5	228.3	3.29E+07	328.7	3196
6	30	5.0	210	6.625	0.4321	15.3	63.2	0.4	3.2	0.4	288.7	4.16E+07	415.8	2021
7	30	2.0	210	6.625	0.2161	30.7	235.4	1.6	11.8	1.6	844.3	1.22E+08	1215.8	5910
8	30	3.4	220	6.625	0.2161	30.7	75.0	0.5	3.7	0.5	425.4	6.13E+07	612.5	3119
9	40	3.4	200	6.625	0.2161	30.7	85.8	0.6	4.3	0.6	508.8	7.33E+07	732.7	3392
10	20	3.4	220	6.625	0.2161	30.7	75.0	0.5	3.7	0.5	425.4	6.13E+07	612.5	3119
11	30	3.4	420	6.625	0.2161	30.7	39.9	0.3	2.0	0.3	236.3	3.40E+07	340.3	3308
12	30	5.0	210	6.625	0.2161	30.7	34.0	0.2	1.7	0.2	298.9	4.30E+07	430.4	2092
13	30	3.4	210	8	0.5229	15.3	318.8	2.1	15.9	2.1	559.0	8.05E+07	805.0	3913

L represents the wavelength measured in feet.

A represents the amplitude measured in feet.

TL represents the total length of curves used for simulation purposes measured in feet.

OD represents the outer diameter of the riser pipe measured in inches.

Wt represents the wall thickness of the riser pipe wall measured in inches.

D/t represents the ratio of the outer diameter to the thickness of the riser pipe wall.

RF represents the reaction force necessary to displace the top of the planar sine wave riser 20 feet.

RFr represents a normalization of the reaction forces to a base case scenario.

K represents the stiffness of the riser model.

Kr represents a normalization of the stiffness to a base case scenario.

PS_{ksi} represents the peak stress in kips per square inch.

PS_{psf} represents the peak stress in pounds per square foot.

$PS_{ksi*100}$ represents the peak stress in kips per square foot multiplied by 100.

L_{30ksi} represents the length of a curved section with necessary to maintain a maximum stress of 30 ksi in the riser.

One important benefit derived from including pre-formed curves 10 is that they add an additional layer of safety for the structural integrity of the whole riser pipe 14. If, for example, the top end of the riser pipe 14 should move beyond its normal operating design limits either horizontally or vertically, the pre-formed curves 10, in various exemplary embodiments, flex, without local buckling, and the riser 14 still maintains structural integrity. This situation might occur if, for example, the floating body 16 should lose buoyancy due to a damaged tank, if the moorings were to come loose or some other mishap were to occur.

In addition to the characteristics of a riser pipe 14 with pre-formed curves 10 shown in the tables above, a number of additional design factors are considered to develop a site-specific design. A non-exhaustive list of these additional factors includes:

- Water depth
- Envelope of surface vessel motion
- Physical properties of the riser
- Ocean currents
- Envelope of deflection curve of the riser to avoid clashing
- Method of installation and removal of riser
- Limitation of curvature of riser to allow passage of through-tubing tools (e.g. "pigs").

The specific embodiments described above and shown in the drawings are given by way of example only. Other aspects and examples of the invention will be understood to be within the spirit of the present invention and with the scope of or equivalent to that described by the claims.